3.0 Engineered Structural Techniques

3.1 Water Management

Diverting surface water from the spoil above the site to decrease the amount of water entering the mined area is highly recommended in acid-producing areas. Channeling surface waters or mine waters to control volume, direction and contact time can be used to minimize the effects of acid mine drainage on receiving streams. The diversion of water from mining areas and from acid-producing materials is an abatement technique used in both surface and underground mines. Surface diversion of runoff involves the construction of drainage ditches to move surface water quickly off the site before infiltration or to limit its movement into the backfill. The diversion is accomplished either by ditching on the uphill side of surface mines or by providing new channels or impervious channels for existing surface streams to convey water across the disturbed area.

Alternatively, pyritic material can be placed where it will be rapidly and permanently inundated, thereby minimizing oxidation of acid-forming materials. Inundation is only suggested where a water table may be re-established to cover acid-producing materials (such as below drainage deep mines) and has not been recommended for surface mined lands or above drainage deep mines in the mountainous Appalachian U.S. region. Complete inundation has been used successfully in other areas where acid-producing materials are submerged in lakes or other permanent impoundments. Other methods of water management involve alkaline loading of water upgradient of mined areas where alkaline water will buffer the effects of subsequent acid water and alkaline loading of the backfill with structured alkaline recharge systems.

3.1.1 Inundation (Saturation)

3.1.1.1 Surface Mine Spoil

The physical saturation of spoil by constructing impoundments within an isolated area of a surface mine has been used to minimize or eliminate AMD. Inundation of acid-producing materials may be a less expensive reclamation technique on some areas than traditional reclamation by backfilling and planting, although the latter are required by law.

Improvements in the quality of impounded waters flowing from acid areas have not always resulted. While pH has not always shown such marked improvement, there has been some reduction in total acid and Fe. Even in the less satisfactory cases, the drainage has had a less deleterious effect on downstream water quality than that from unreclaimed areas. The creation of an impoundment in the final cut of a surface mine not only lowers the cost of reclamation, but also has several other advantages. It forms recreation areas, aids in recharging the water table in the local area, and can eliminate or greatly reduce the amount of pollution from acid mine drainage and silt. By carefully designing the impoundment size and depth so the body of water formed will cover all acid-producing and carbonaceous materials, and also completely flood any intercepted deep mine workings or auger mining holes, the pyrite oxidation process will be stopped and thus the formation of acid will cease. Field studies have confirmed this action, and have also shown that the resulting impoundment quickly flushes the oxidized acid salts from the contacted area and produces a body of water of near neutral to alkaline quality.

Case Studies:

Perry et al. (1997) found that acid-producing materials placed in a seasonal water table produced acid drainage in the eastern coal fields of the U.S. Intended placement above the water table was not accomplished. Perry provided field validation for previous laboratory studies (Leach 1990) which found that fluctuating water tables or partial flooding produced worse drainage than that predicted for either "dry" or submerged placement.

3.1.1.2 Underground Mines

Inundation of an underground mine can be an effective method of decreasing AMD by depriving pyrite of oxygen. In addition, if overlying rocks contain carbonate minerals, flooding can provide additional alkalinity by increasing the volume of alkaline strata in contact with mine water and increasing the residence time so that chemical equilibrium is more closely approached. On the other hand, if the mine walls contain readily soluble oxidation products of the sulfides, then the water quality draining from the mine can get worse.

A wet mine seal is a wall across a draining mine entrance that allows flow of water through the seal but prevents air from entering the mine. A dry mine seal is a wall across a mine entrance where water does not drain from the entrance. To the extent that the seal raises the water level in the mine and inundates the workings, the production of AMD can be inhibited. Although complete blockage of adits at the down-dip side of underground mines has been attempted in order to prevent drainage and raise the water level in the mine, this procedure has commonly led to breakout of the water, sometimes explosively, either at the seal or at nearby locations. The placement and construction of mine seals, therefore, must be carefully planned and executed.

Case Studies:

Case study summary is not available at this time.

3.1.1.3 Coal Refuse

The disposal and placement of acid-producing coal refuse in a saturated condition to limit its exposure to air and water has been used for decades with mixed results. Many coal slurry impoundments have been constructed for disposal of pyritic materials near coal preparation plants. In most cases, oxidation and generation of acid products are stored in the slurry impoundment and are released as water drains from the impoundment. Many coal refuse disposal sites must treat the drainage with chemicals before discharge.

Case Studies:

Case study summary is not available at this time.

3.1.1.4 Reactive Tailings

Disposal of sulfide tailings under a water cover, such as a lake or fjord, has been used extensively as another way to prevent acid generation by excluding oxygen to sulfides. Wet covers also include flooding of above ground tailings ponds. Deposition of sulfide tailings under water has been used at various mines in Canada and Norway.

Case Studies:

Case Studies are reported in the Metals Mining Handbook.

3.1.2 Dewatering

Removing water, one of the principal reactants in pyrite oxidation, should theoretically stop the production of AMD. With no water to move reaction products from the surfaces of pyrite, no contamination of waters should occur. While this can be done in a laboratory setting, the total and complete removal of water in nature is nearly impossible and therefore the complete control of AMD, even in dry situations or climates, does not occur. However, reducing the amount of water contacting pyritic material and containing water that is in contact with acid-producing materials may reduce the impacts of AMD to off site water bodies and streams.

Case Studies:

Norton (1987) designed and constructed a series of peripheral deep wells to dewater abandoned deep mines adjacent to the Crouch Mining - Dahlquandy surface mine (UK) to allow the water to be discharged without treatment. This mine is one of the largest open cast mines in the UK. Pit water quality from nearby surface mines was sufficiently degraded by oxidation of coal fines on the pit floor that chemical treatment was required. The quality of water pumped from the wells was alkaline and metal concentrations were low enough that the water could be discharged to receiving streams without treatment. Another benefit was the working conditions in this pit were greatly improved with respect to water management.

3.1.3 Drains

Draining water away from pyritic materials as rapidly as possible may keep water from reacting and forming acid products. Various types of drains may be used to convey water out of the backfill or away from acid-producing materials, or coarse materials placed around tightly-packed pyritic materials may take water away from these acid-producing materials.

3.1.3.1 Porous Envelope

A porous envelope effect may occur in groundwater systems when mine tailings of low permeability are placed within high-permeability soils and overburden within or on a

backfill. If the permeability contrast between the tailings and the surrounding material is large, groundwater will flow around the tailings mass rather than through it, and metal leaching will be minimized.

Case Studies:

Case studies are reported in the Metals Mining Handbook.

3.1.3.2 Chimney, Highwall, French, Blanket Drains

Drains can be installed in various places to move water from one area to another. Chimney drains collect water from a backfill or valley fill and convey the water through a long, high, column of hard, coarse sandstone. Highwall drains collect water from the highwall along permeable channels of sandstone or limestone. French drains are small, distinct constructed channels in disturbed rock, usually along the pavement, where water is directed to flow out of the fill. Blanket drains are constructed by forming a coarse, permeable rock covering along the entire fill bottom to allow drainage water to move out of the fill through the base. All of these methods are reliable methods for moving water from spoil, refuse, and fills.

Case Studies:

Geidel and Caruccio (1984) used a blanket drain in a hydrologically isolated surface mine to evaluate it's effectiveness in reducing AMD. Even though the pavement had been treated with lime, the water flowing through the drain and across the pavement provided a favorable environment for AMD formation.

3.2 Impervious Soil Cover or Membrane

Dry barriers are constructed from natural or man-made materials that retard the movement of water and oxygen into areas containing acid-producing rock. Barriers can achieve substantial reductions in water flow through piles, but generally do not control AMD completely.

Plastic liners are rarely used in mining because covering the large volumes of waste with a liner is usually too expensive. However, this method may be appropriate in settings where isolation of small pods of acid-producing material is possible.

Case Studies:

At the Upshur Mining Complex in West Virginia, Meek (1994) reported covering a 20-ha spoil pile with a 39-mil PVC liner. This treatment reduced acid loads by 70%.

A cover system was developed for a coal refuse disposal area in Illinois (Gentile et al. 1997). The system comprised a graded and compacted refuse layer, overlain by a compacted clay liner, and a protective soil cover. Infiltration was reduced by about 18% initially compared to an unreclaimed refuse surface. Over time it is predicted that the cover should reduce infiltration by 84%.

3.3 Underground Mine Sealing

Throughout most of the Appalachian coal fields, abandoned underground mines are considered to be the principal source of AMD pollution. This perception is based on the sheer number of abandoned underground mines, the number of very large acreage abandoned mines, and the fact that most older mines were developed updip to promote gravity drainage. The AMD problems associated with older underground mines can be increased by inadequate barrier pillars between mines, inadequate outcrop barriers, and hydraulic interconnection of adjacent mine complexes and/or connection of superimposed mines.

While AMD problems associated with some of these older mine complexes can be addressed by remining of the abandoned mine complex, this option is not economically viable for a majority of abandoned mine complexes in the Appalachian coal fields. Mine sealing can, in many instances, be an effective and economically viable means of eliminating or minimizing the AMD pollution associated with abandoned underground mines.

Regulators were faced with the numerous gravity drainage deep mines that contributed to an ever increasing AMD pollution problem. They responded by requiring that deep mines be sealed at closure to ensure public health and safety. For example, the Commonwealth of Pennsylvania passed the "Bituminous Coal Mine Act" in 1961, which mandated that all permanently abandoned mines be plugged, sealed or filled.

In 1977, Office of Surface Mining (OSM) regulations on deep mine surface facilities and entry closure became law. In 1978, the Mine Safety and Health Administration (MSHA)

adopted regulations which further defined the procedures and conditions for sealing an abandoned underground mine. Currently, nearly every federal and state agency that regulates deep mining has adopted some regulations mandating mining down-dip and mine sealing at closure to minimize AMD effects and to ensure the health and safety of the public. Conversely, throughout much of the rest of the world, the practice of mining up-dip to facilitate gravity drainage continues unabated.

Deep mine sealing is defined as closure of mine entries, drifts, slopes, shafts, boreholes, barriers, outcrops, subsidence holes, fractures and other openings into underground mine complexes. Deep mine seals are constructed to achieve one or more functional design goals including: 1) eliminate potential access to the abandoned mine works following closure, 2) minimize AMD production by limiting infiltration of air and water into the deep mine, 3) minimize AMD production by maximizing inundation of the mine works, 4) minimize AMD exfiltration through periphery barriers to surface water systems, and 5) develop staged internal mine pools to regulate maximum hydraulic head and pressure. The primary factor affecting the selection, design and construction of underground mine seals is the anticipated hydraulic pressure that the seal will have to withstand when sealing is completed.

3.3.1 Surface Access Dry Seals

Surface access seals are installed in entries (drifts, slopes, shafts and subsidence areas) where little or no hydrostatic pressure will be exerted on the seals. The primary functions of the seals are to eliminate potential access to the abandoned mine works following closure and to decrease AMD production by limiting infiltration of air and water into the deep mine. Typically, these seals are installed in entries positioned in the structurally upgradient areas of the mine where the majority of the mine works lie "below" the mine seal site. These seal areas are often backfilled from the front side of the seal to the ground surface and then the seal backfill areas are stabilized, amended, resoiled and revegetated. These seals have good long term effectiveness due to the lack of hydraulic head (pressure) on the seals (Figures 3.1 and 3.2).

Surface access seals have been used extensively throughout the world. The lack of hydraulic head allows these seals to be both simple in construction and low cost.

Surface access seals are typically constructed using concrete block or masonry, although more recent surface seals have been constructed using compacted clay and concrete-flyash mixtures.

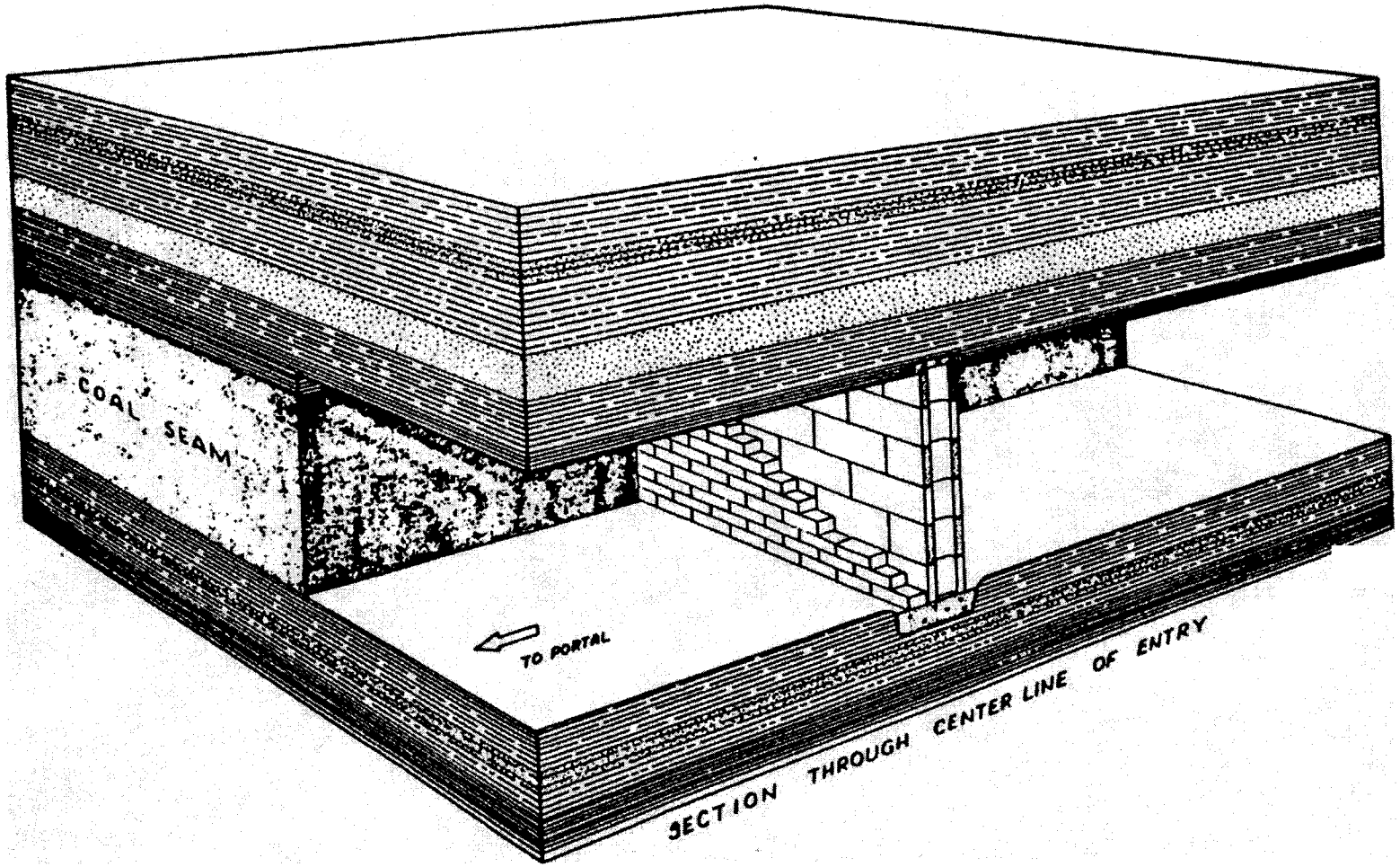
3.3.2 Air Trap Seals

Air trap seals are installed in mine entries where mine discharges flow from the mine. Conventional mine sealing using air-trap seal methods began in the 1920's and was used extensively in the 1930's in the U.S. in conjunction with the Works Project Administration (WPA) mine sealing efforts. The primary functions of these seal types are to eliminate potential access to the abandoned mine works following closure and to minimize AMD production by limiting infiltration of air and water into the deep mine.

The initial appeal of the air-trap sealing system was that this was a simple, low-cost sealing approach, which still allowed water to discharge without affecting the mine seal integrity. Construction was almost always using concrete blocks (Figures 3.3 and 3.4). In a typical air-trap sealing program, surface access seals were first constructed in the upgradient mine entries (which were sometimes backfilled), and then the air-trap seals were constructed in the downgradient mine entries where water historically discharged from the mine.

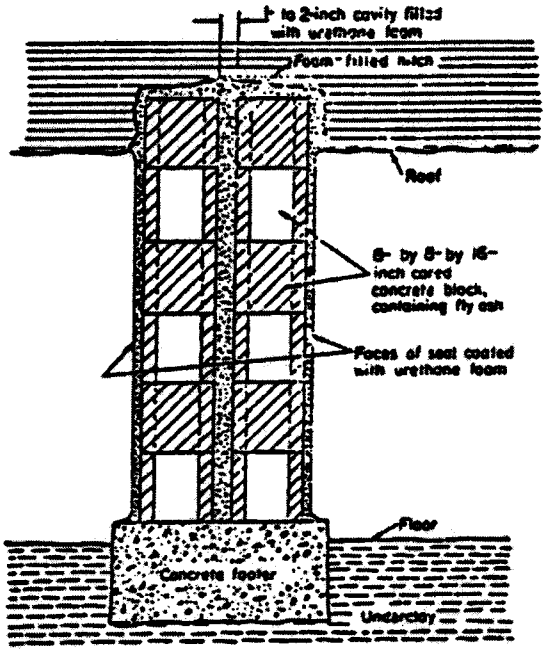
Unfortunately, the long term effectiveness of this sealing method was generally poor. Failures of these seals usually occurred when rock, wood, debris and sediment clogged the air-trap. This restricted outflow from the mine causing increases in volume and head of the impounded water in the mine. The subsequent increase in pressure caused many of these seals to collapse.

A study done by the US Bureau of Mines (Borek et al. 1991) showed that 14 mine seals installed in 1967 were all intact and only a few small leaks from weir walls were noted. Acidity and metal concentrations decreased over time, but this decrease may be due to a natural decrease or to the seals. Based on measurements taken after sealing and several times since then, pH values slightly increased over time.

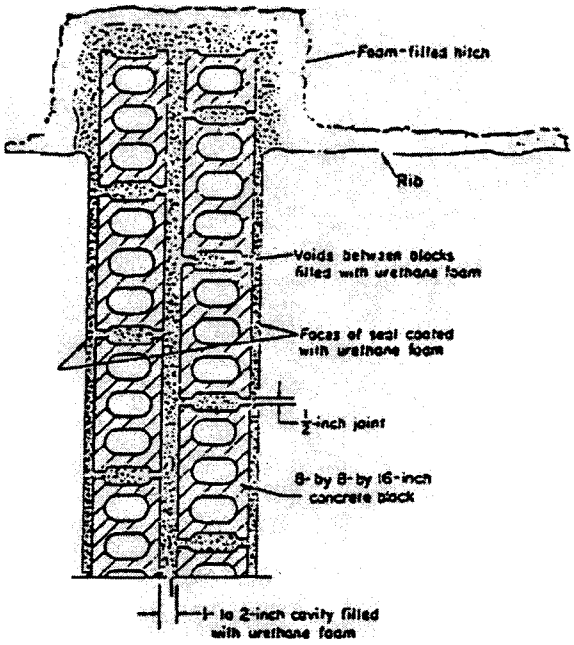


Typical Masonry Seal
Air Seal - Ventilation Stopping

Figure 3.1

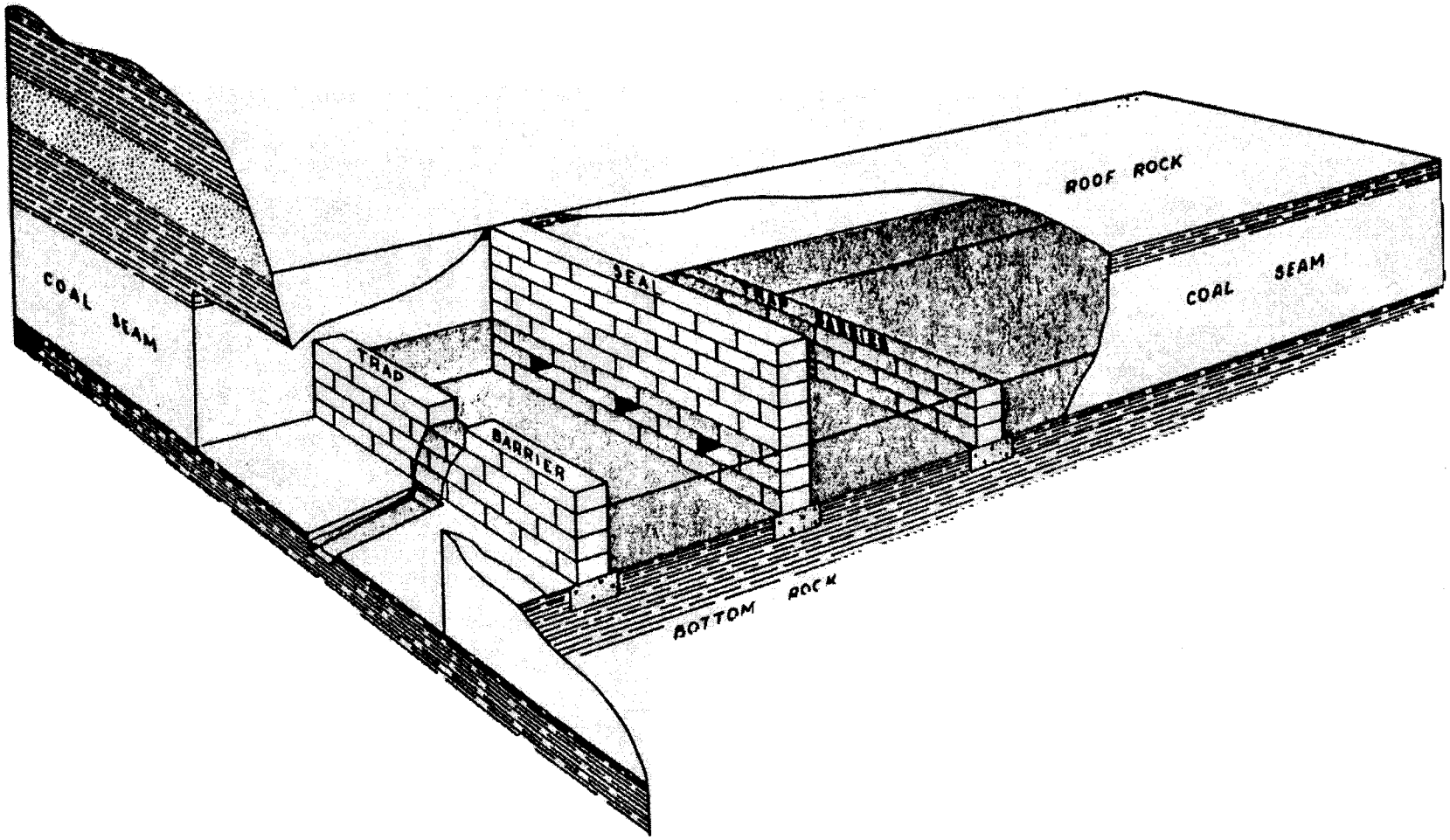


Cross-Sectional View of Masonry Seal Showing Method of Construction, Hitching Into Roof, and Concrete Footer.



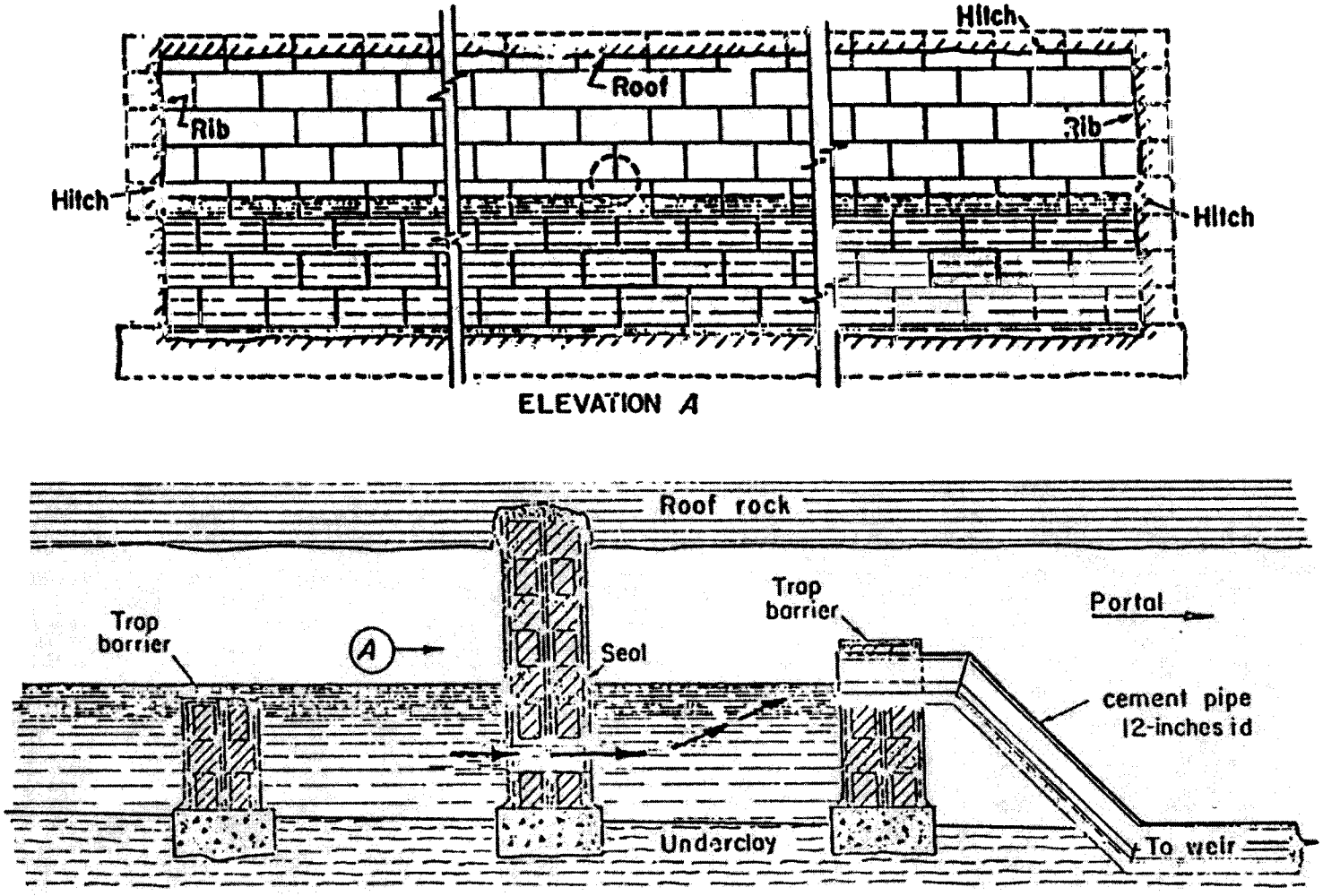
Top View of Masonry Seal Showing Method of Construction and Hitching Into Rib.

Figure 3.2



Conventional Type Air Seal with Discharge

Figure 3.3



General Arrangement of a Wet Seal With Air Trap.

Figure 3.4

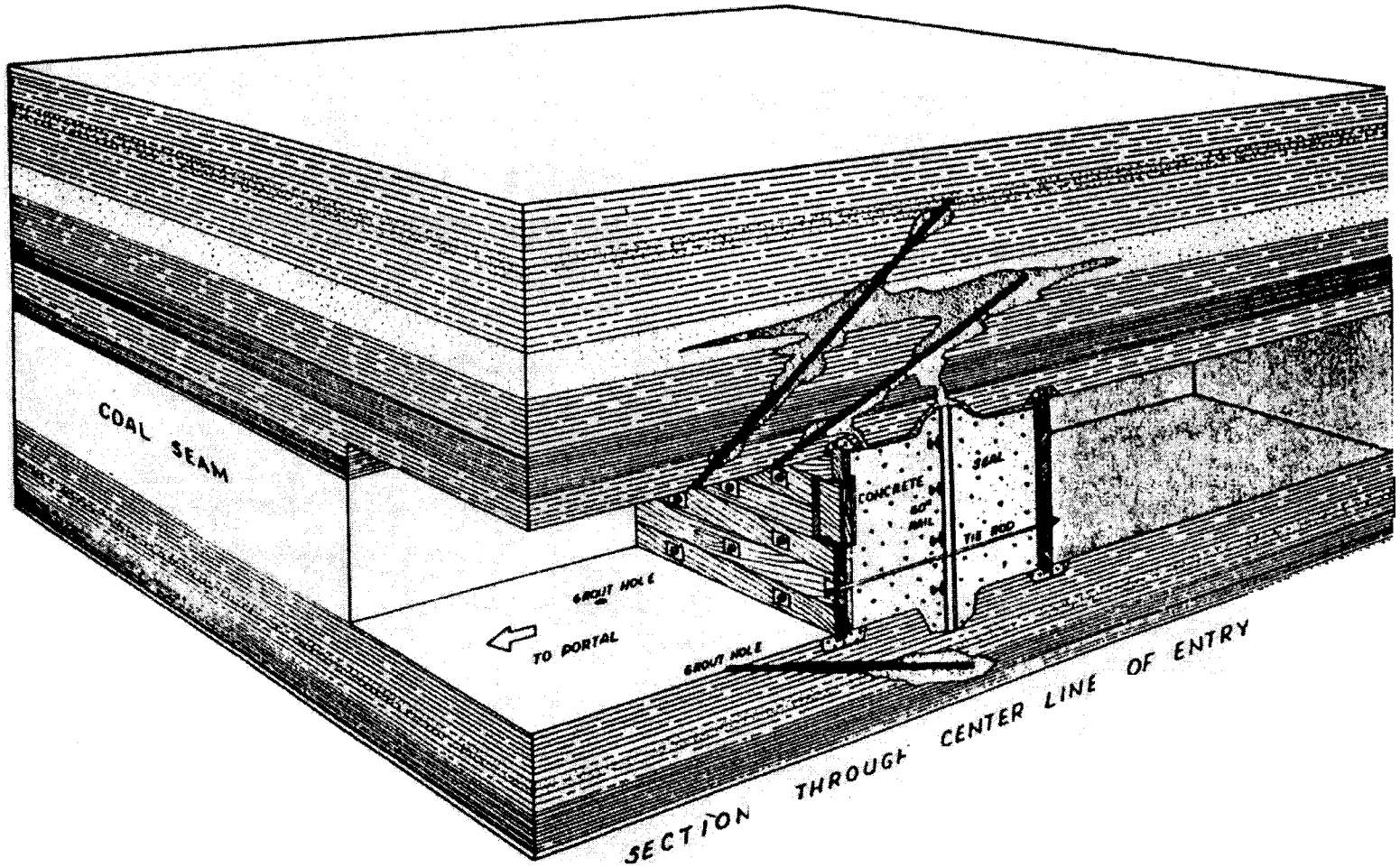
3.3.3 Hydraulic Mine Seals

Currently, most underground mine seals being constructed are hydraulic mine seals although surface access seals are still used in "no water, no head" situations for economic reasons. The numerous, long term failures of the air-trap seal systems coupled with the inability of this design to withstand significant hydraulic pressures has caused these seals to become obsolete. Hydraulic mine seals are installed in entries (drifts, slopes, shafts and adjacent strata) where significant hydrostatic pressure will be exerted on the seals. The primary functions of the seals are to eliminate potential access to the abandoned mine works following closure, to minimize AMD production by limiting infiltration of air and water into the deep mine, and to minimize AMD production by limiting exfiltration of water and maximize inundation (Figures 3.5 and 3.6). Further, hydraulic mine seals have been constructed to repair/replace breached areas of coal barrier pillars and to provide "constructed internal barriers" in sections of the mine complex to minimize AMD exfiltration through coal barrier pillars to adjacent flow systems and develop staged internal mine pools to regulate maximum hydraulic head and pressure. The primary goal in the design and installation of hydraulic mine seals is to construct a mine seal system that serves as a structural bulkhead and acts as a water tight dam capable of withstanding the maximum hydrostatic head that may develop as a result of the flooding of the mine complex. A secondary consideration in the design and siting of hydraulic mine seals is the hydrologic performance of the seal. The adjacent stratum has natural joints, bedding planes and subsidence cracks (from mining) that may serve to transmit significant water around the mine seal area. Thus, while the structural design will specify a minimum required thickness necessary to safely impound the water at design heads and pressures, the potential for water to migrate around the mine seal area through adjacent strata must be compensated for in the design.

Typically, three common and successful approaches are used separately or in combination to minimize the potential migration of impounded water around the mine seal area. These are:

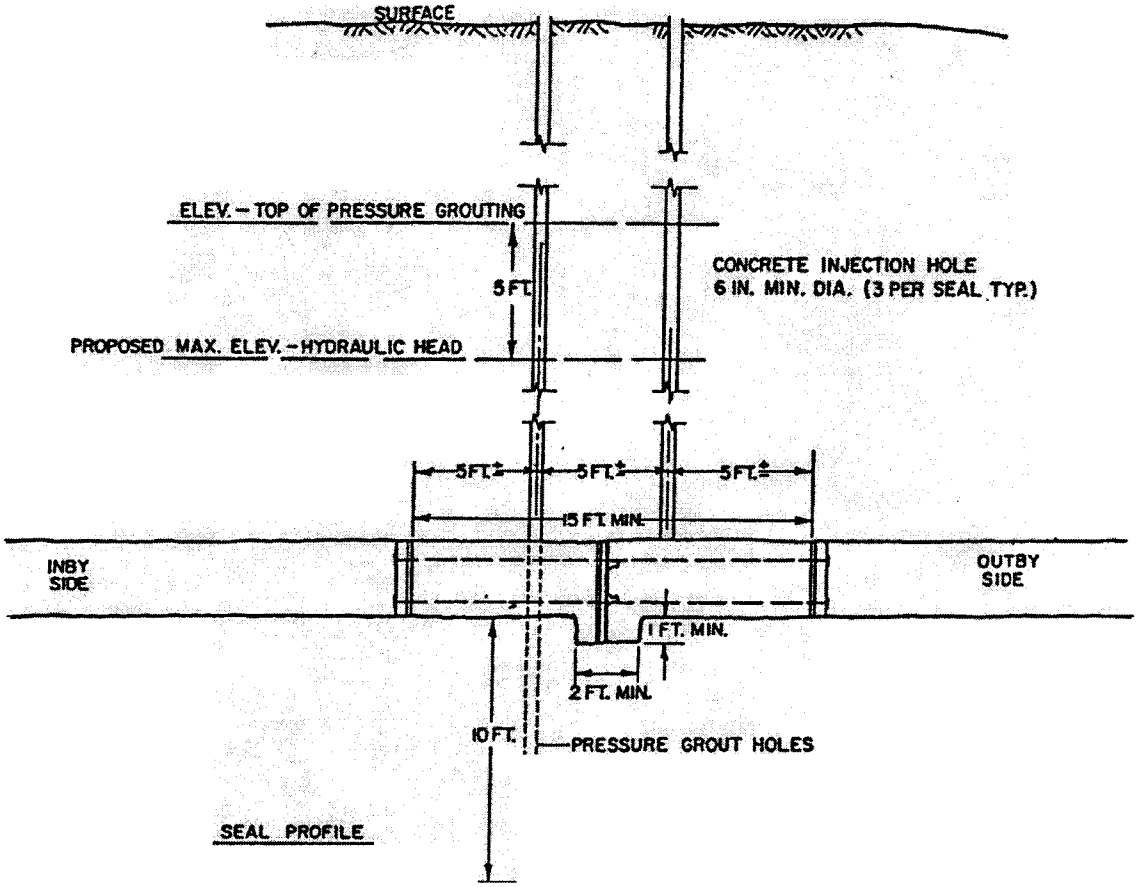
1. Pressure grouting of the adjacent strata - this process injects grout into the natural and mining related cracks in adjacent strata thus minimizing migration of water past the seals.
2. Increase mine seal thickness - this increases "flowpath distance" that migrating water must travel to bypass the seals and greatly increases the safety factor for the structural design.
3. Install secondary mine seals - provides redundant mine seals to limit potential migration around seals. This approach is mostly limited to very high head sites due to the high costs.

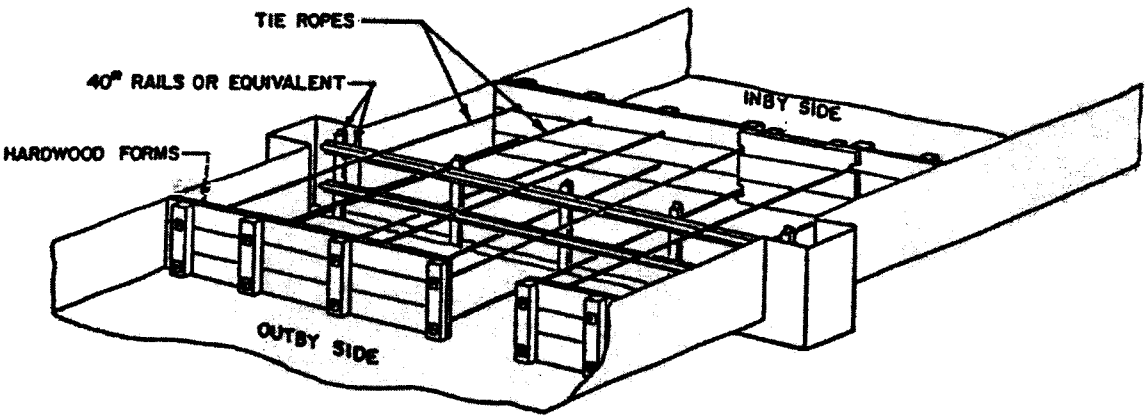
Another fundamental design consideration in the siting of mine seals is the accessibility of the mine entries where the seals are to be constructed. In most abandoned mines and in areas of active mines where conditions are unreasonable or unsafe, mine seals can be remotely placed through drill holes (Figures 3.7 to 3.10).



Deep Mine Hydraulic Seal -
Underground Barrier Dam

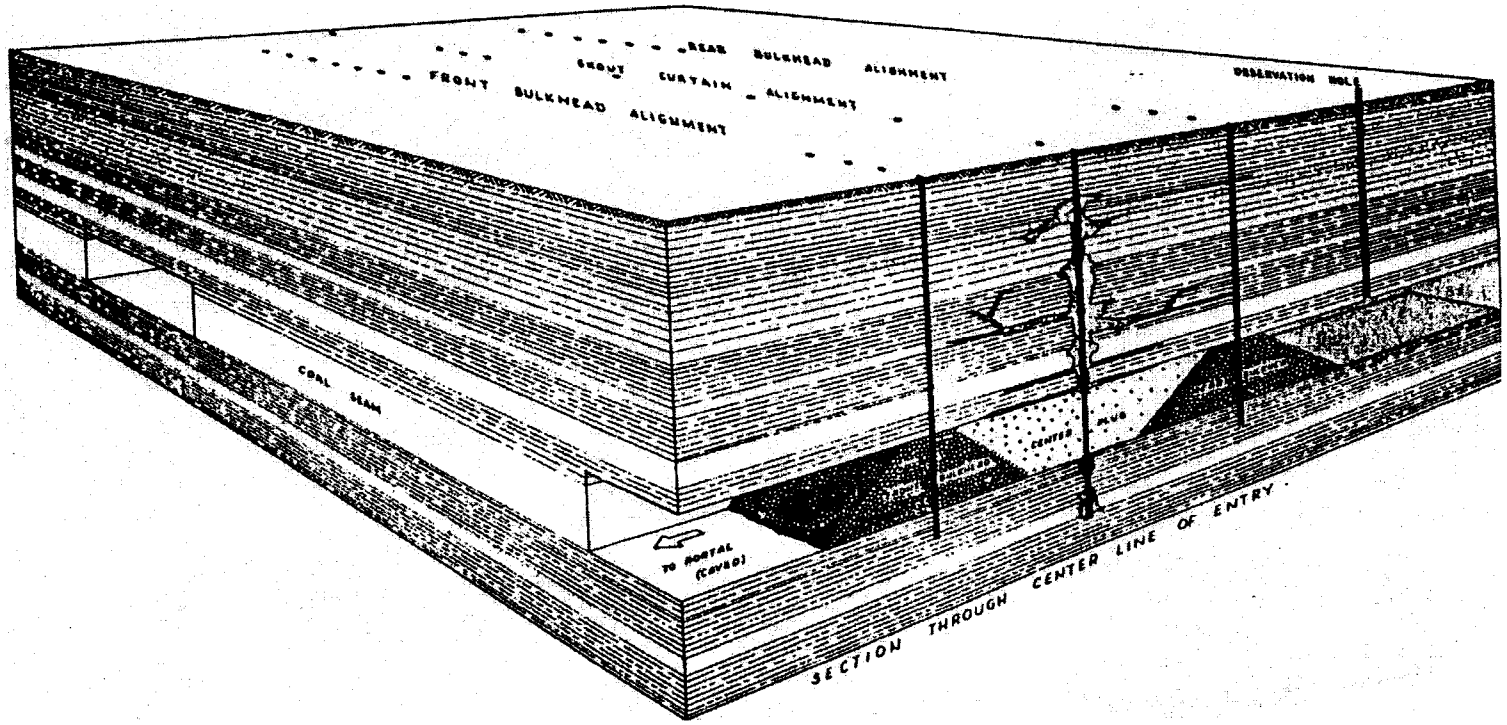
Figure 3.5





MINE SEAL FORM DETAILS PRIOR TO INSERTION OF CONCRETE

Figure 3.6



Deep Mine Hydraulic Seal By Remote Installation

Figure 3.7

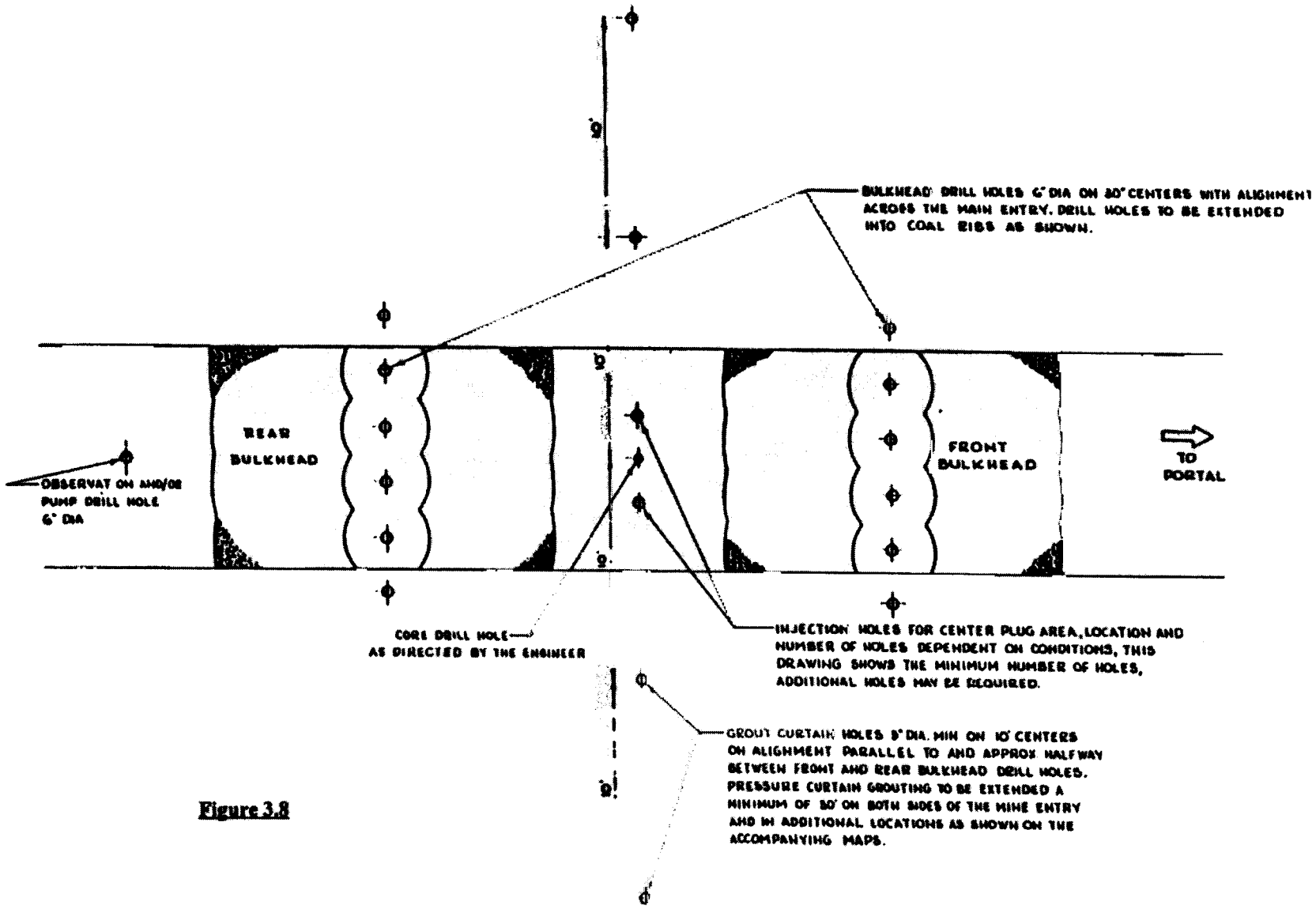
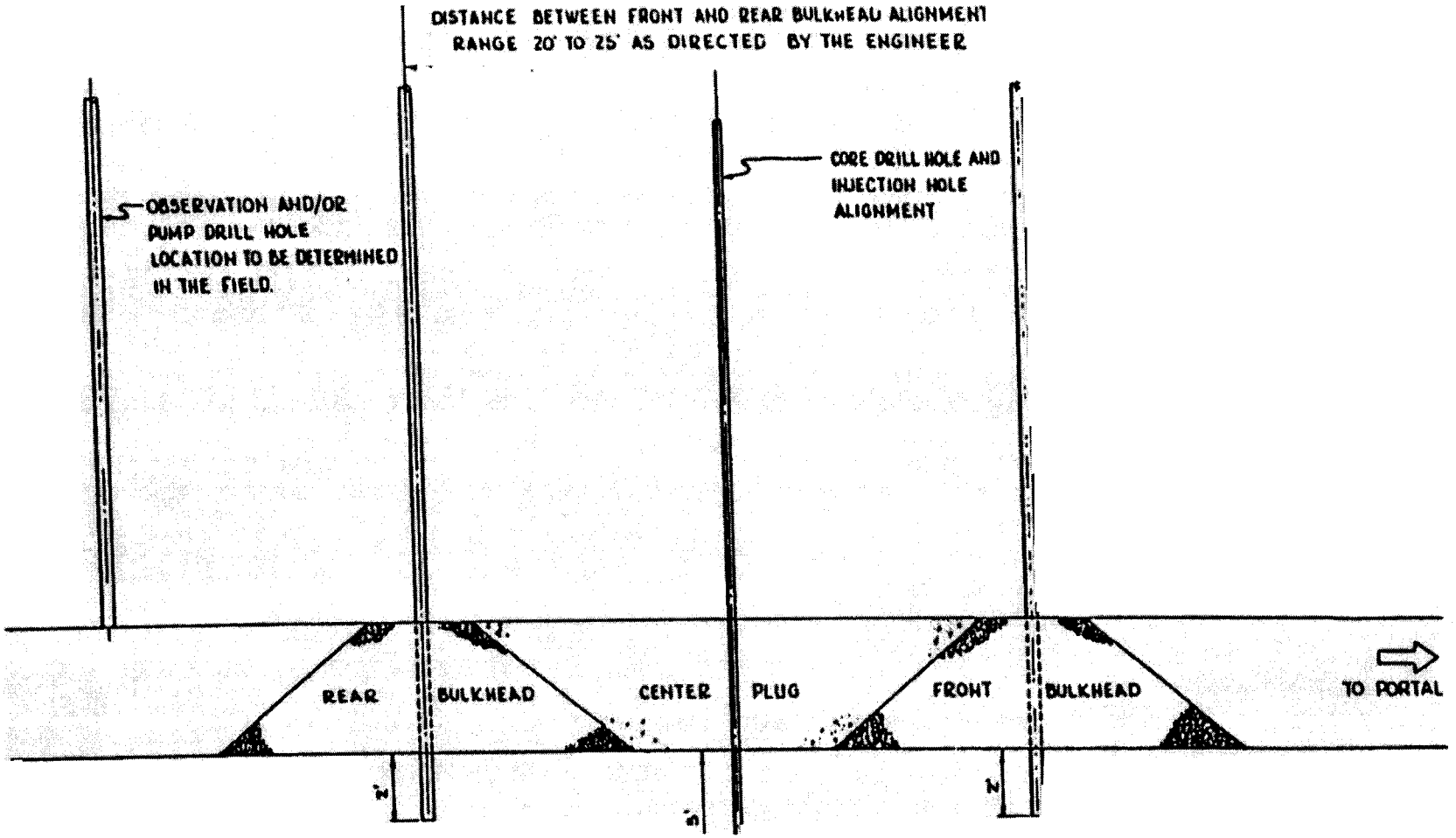
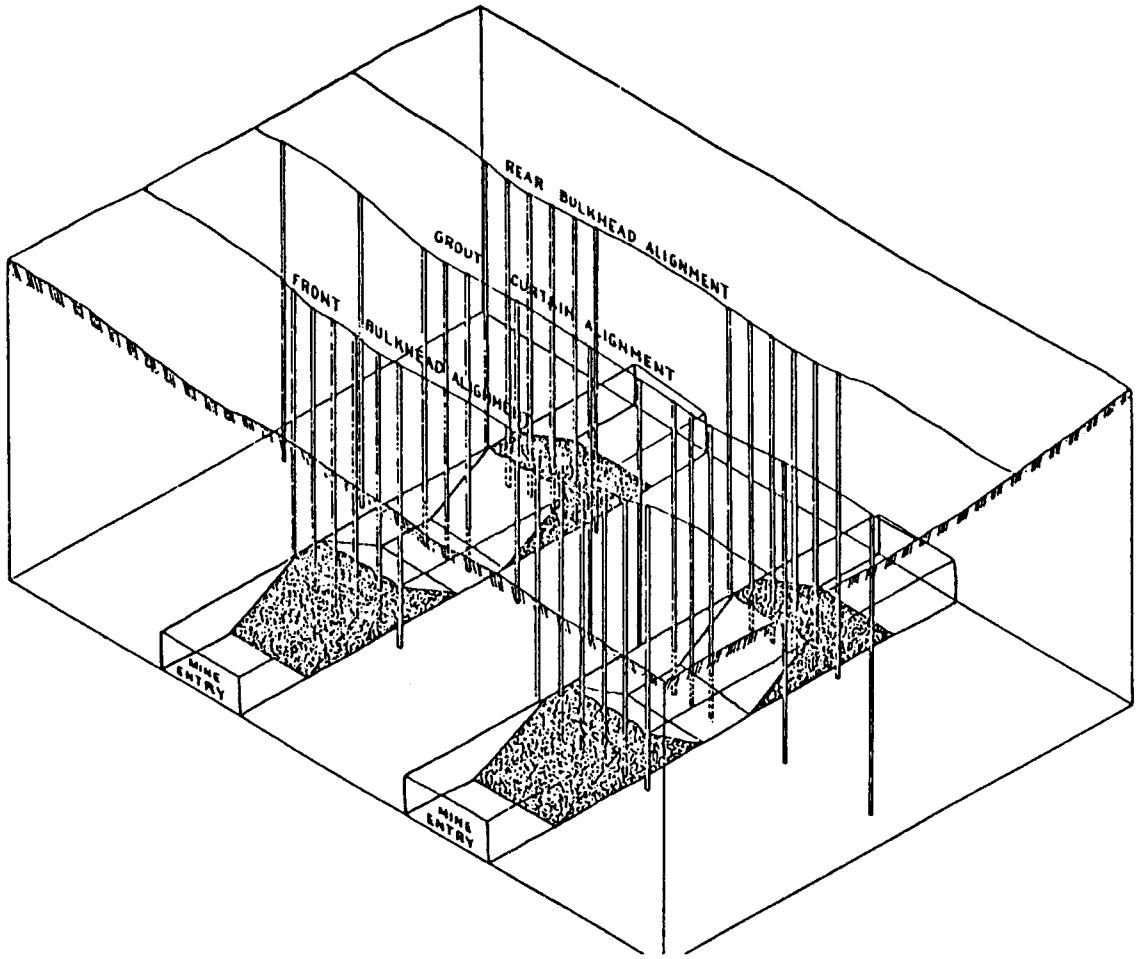

BULKHEAD DRILL HOLES 6" DIA ON 30" CENTERS WITH ALIGNMENT ACROSS THE MAIN ENTRY. DRILL HOLES TO BE EXTENDED INTO COAL RIBS AS SHOWN.
REAR BULKHEAD
FRONT BULKHEAD
TO PORTAL
OBSERVAT ON AND/OR PUMP DRILL HOLE 6" DIA
CORE DRILL HOLE AS DIRECTED BY THE ENGINEER
INJECTION HOLES FOR CENTER PLUG AREA, LOCATION AND NUMBER OF HOLES DEPENDENT ON CONDITIONS, THIS DRAWING SHOWS THE MINIMUM NUMBER OF HOLES, ADDITIONAL HOLES MAY BE REQUIRED.
GROUT CURTAIN HOLES 8" DIA. MIN ON 10' CENTERS ON ALIGNMENT PARALLEL TO AND APPROX HALFWAY BETWEEN FRONT AND REAR BULKHEAD DRILL HOLES. PRESSURE CURTAIN GROUTING TO BE EXTENDED A MINIMUM OF 50' ON BOTH SIDES OF THE MINE ENTRY AND IN ADDITIONAL LOCATIONS AS SHOWN ON THE ACCOMPANYING MAPS.

Figure 3.8



Construction Drawing of Deep Mine Seal

Figure 3.9



Isometric Drawing of Deep Mine Seals
No Scale

Figure 3.10

3.3.3.1 Hydraulic Mine Seals - Drift Areas

Mine drifts are horizontal entries allowing the deep mine to be accessed from the surface. Typically, the selection of mine seal design is based on the anticipated maximum pressure and the choice of construction materials used for the seals is an economic decision. Generally, drift seals at active mine sites are constructed in surface accessible areas and thus these mine seals are rarely constructed using remote placement construction methods unless severe subsidence is occurring or believed to be possible. Conversely, drift seals at abandoned mine sites are typically unsafe and often constructed using remote methods.

Case Studies:

Foreman (1964) designed and constructed the first known remotely placed, double bulkhead mine seal at an abandoned deep mine with a pollutional discharge situated in Blair County, PA. The seal eliminated the pollutional discharge and proved that mine seals could be effectively placed using remote methods. Foreman, Bullers and Hong (1969) constructed 69 remotely placed, deep mine seals at Moraine State Park (Butler County, PA). These seals were constructed to abate AMD discharges emanating from 22 abandoned mine complexes which drained to Lake Arthur. Maksimovic and Maynard (1982) performed a follow-up assessment of the mine sealing and concluded that total mean discharge, alkalinity, and Fe increased while total mean acid loads decreased. Overall, they found mine sealing improved the water quality of Lake Arthur.

Foreman, Ward and Bullers (1970) constructed 32 remotely placed, deep mine seals at the Argentine/Whiskerville project area (Butler County, PA). These seals were constructed to abate AMD discharges emanating from several abandoned mine complexes draining to Slippery Rock Creek. Followup hydrogeologic and geochemical assessment of the mine sealing by state engineers concluded that the mine seals were functioning and the mine achieved about 6 m of inundation before reaching equilibrium without any AMD discharge to Slippery Rock Creek..

Foreman, Hong and Foreman (1979) designed and constructed a large clay dike and 35 hydraulic drift seals at Lake Hope State Park in Zaleski National Forest (Vinton County, OH). These seals were constructed to abate severe AMD discharges emanating from six

abandoned deep mine complexes draining to Lake Hope. Nichols et al. (1983) performed a followup assessment of the mine sealing and reported an increase in pH of nearly 2 units and corresponding decreases in conductance (25%), sulfates (40%) and total Fe (84%). Subsequently, Lake Hope has improved to the point where a viable bass fishery has been reestablished.

Beck and Foreman (1985) constructed and evaluated six concrete seals installed at the Oneida Mining Co. - Dilltown facility (Indiana County, PA) designed to prevent a post-mining AMD discharge from the mine after closure and inundation. A later assessment of the mine seals concluded that the seals were effective with no discharge found and no impact to underlying groundwater systems.

3.3.3.2 Hydraulic Mine Seals - Slopes

Mine slopes are angular entries allowing the deep mine to be accessed from the surface. Typically, the selection of mine seal design is based on the anticipated maximum pressure, and the choice of construction materials used for the seals is an economic decision. Generally, slope seals at active mine sites are constructed in surface accessible areas. Thus these mine seals are rarely constructed using remote placement construction methods unless severe subsidence is occurring or believed to be possible. Conversely, slope seals at abandoned mine sites are typically unsafe and often constructed using remote methods.

Case Studies:

Foreman and Foreman (1985) designed and constructed two concrete slope seals installed at the Island Creek Coal Co. - Bird #2 and Bird #3 deep mines (Cambria and Somerset Counties, PA) to prevent or minimize post-mining AMD discharges from the slope following closure and inundation. No post-construction discharge has been identified from the slope.

Foreman and Foreman (1992) designed and constructed a concrete slope seal, which was installed at the PA Mines Corp. - Rushton deep mine (Centre Co. & Clearfield Co., PA), to prevent or minimize post-mining AMD discharge from the slope following closure and inundation. No post-construction discharge has been identified from the slope.

3.3.3.3 Hydraulic Mine Seals - Shafts

Mine shafts are vertical entries allowing the deep mine to be accessed from the surface. Typically, the selection of mine seal design is based on the anticipated maximum pressure, and the choice of construction materials used for the seals is an economic decision. Generally, shaft seals at active mine sites are constructed in surface accessible areas and thus these mine seals are rarely constructed using remote placement construction methods unless severe deterioration is occurring or believed to be possible. Conversely, shaft seals at abandoned mine sites are typically unsafe and often constructed using remote methods.

Case Studies:

Beck and Foreman (1985) constructed and evaluated a concrete shaft seal installed at the Oneida Mining Co. - Dilltown facility (Indiana County, PA), which was designed to prevent a post-mining AMD discharge from the mine after closure and inundation. The assessment of the shaft seals concluded that the seal was effective with no discharge found and no impact to underlying groundwater systems.

Foreman, Beck and Foreman (1984) constructed and evaluated a concrete shaft seal installed at the PA Mines Corp. - Lady Jane Collieries deep mine. The shaft seal was effective with no discharge found and no impact to underlying groundwater systems.

Foreman and Foreman (1985) designed and constructed seven concrete shaft seals installed at the Island Creek Coal Co. - Bird #2 and Bird #3 deep mines (Cambria and Somerset Counties, PA) following closure. No post-construction discharge has been identified from the shaft.

Foreman and Foreman (1992) designed and constructed a concrete shaft seal installed at the PA Mines Corp. - Rushton deep mine (Centre and Clearfield Counties, PA) following closure. No post-construction discharge has been identified from the shaft.

3.3.3.4 Hydraulic Mine Seals - Coal Barrier Pillars

Coal barrier pillars are intact blocks of coal left unmined to provide hydraulic barriers for water management as well as to assist in ventilation and roof support. Occasionally, coal barrier pillars are breached during active operations and need to be repaired to return them to original condition. Coal barrier pillars can be classified as peripheral barriers (intact coal

at the edge of the deep mine works) or internal barriers (intact coal located in the interior of the mine works). Generally, both peripheral and internal coal barrier pillars at active mine sites are accessible and thus hydraulic barrier seals installed at these mine seals are rarely constructed using remote placement methods unless the area is flooded or is abandoned. Typically, peripheral barriers at abandoned mine sites are accessible if the barriers are situated above regional drainage levels. Conversely, both peripheral barriers below regional drainage and internal barriers at abandoned mine sites are typically unventilated and often flooded making them unsafe. These are often constructed using remote methods.

Peripheral coal barrier pillars are often limiting factors in the design of mine seals for abandoned mines, particularly along downgradient outcrop areas of mines situated above regional drainage levels. Further, internal coal barrier pillars are often limiting factors to achieving maximum inundation in upgradient mines where significant recharge potential exists for water movement through the barrier to adjacent, downgradient mine works.

Case Studies:

Foreman, Hong and Foreman (1979) constructed a large clay dike and 35 hydraulic drift seals at Lake Hope State Park in Zaleski National Forest (Vinton County, OH). This mine sealing project was undertaken to abate severe AMD discharges emanating from six abandoned deep mine complexes which drained to Lake Hope. The clay dike was constructed to continuously replace the inadequate downgradient outcrop barrier along the edge of the mine. The functional repair of the barrier allowed the mine complex to achieve full inundation when coupled with the construction of the mine seals. Nichols et al. (1983) found an increase in pH of nearly 2 points and corresponding decreases in conductance (25%), sulfates (40%) and total Fe (84%). Subsequently, Lake Hope has improved and a viable bass fishery has been reestablished in the Lake.

Foreman and Foreman (1985) constructed a concrete mine seal in the breached barrier of the active Island Creek Coal Co. - Providence #1 deep mine (Webster County, KY) to reestablish the functional aspect of the barrier and return the mine to active production. The miners at the Providence deep mine had inadvertently mined through the barrier into the adjacent, abandoned Hall-Luton #9 deep mine which was fully flooded at that time. The resultant inflow flooded over 60% of the Providence mine causing full evacuation of the

workforce and complete destruction of most of the ventilation stoppings in the mine. Because of the presence of an overlying, flooded mine complex, the cost of placing remote seals was deemed excessive and it was decided to renovate the immediate section and construct the mine seal at the face. The MSHA approved mine sealing was totally successful and allowed the mine to be reopened and returned to full productivity.

Foreman, Moore and Foreman (1982) designed and constructed a remotely placed, deep mine seal in an entry which breached the peripheral barrier of the Guarnieri deep mine complex for the Adobe Coal Mining Company (Lawrence County, PA) to restore the function of the barrier and eliminate drainage of the deep mine reservoir into the active surface mine pit adjacent to the mine. Following construction, the drainage was abated and Adobe was able to surface mine without further inflows from the adjacent deep mine reservoir.

Foreman, Hong and Ward (1977) designed and constructed a slurry trench to abate the discharge from an abandoned deep mine (Mercer County, PA). The slurry trench was developed along the peripheral outcrop barrier of the mine and was excavated from the surface using large backhoes. The trench was then backfilled with a soil-bentonite stabilized slurry which provided a hydraulic barrier to prevent lateral discharge from the abandoned deep mine. The slurry-trench seal was effective since there was no discharge following construction and the deep mine became fully inundated.

Foreman and Glenn (1980) designed and constructed a slurry trench to abate the discharge from an abandoned deep mine (Clarion County, PA). The slurry trench was developed along the peripheral outcrop barrier of the mine and was excavated from the surface using large backhoes. The trench was then backfilled with a stabilized soil-cement slurry which, when set-up, provided a relatively impervious barrier to prevent lateral discharge from the abandoned deep mine. The slurry-trench seal was effective since there was no discharge following construction and the deep mine became fully inundated.

3.3.4 Flowing Artesian Wells

Flowing artesian wells are wells that overflow onto the ground surface and then flow overland to surface drainage features such as streams, rivers or lakes. Historically, some flowing artesian wells were developed to supply water without pumping. Flowing artesian wells occur when the ground surface elevation of the well is lower than the equivalent

elevation (pressure head) of the flow system into which the well was developed. The pressure head in the flow system attempts to reach equilibrium with atmospheric pressure and becomes the driving force that causes water level to rise in the well and overflow from the well.

Flowing artesian wells and their flow system are developed into confined areas, typically by overlying strata which have very low hydraulic conductivity. The drilling operation punctures this confining stratum and allows the water to rise. The scope of AMD problems associated with flowing artesian wells range from minor pollutional effects such as slightly elevated metals concentrations associated with natural flow systems to major pollutional discharges which are directly connected to significant sources of AMD such as abandoned deep mine pools. In fact, many major pollutional discharges from flowing artesian wells are linked to improperly sealed deep well drilling associated with oil and gas development.

Sealing abandoned and newly drilled flowing artesian wells can be an effective and economically viable means of eliminating or minimizing AMD pollution associated with flowing artesian wells. The technical approach to design and construction of seals for flowing artesian wells is dictated by the pressure and hydraulic conductivity of the flow system in which the well was developed. For purposes of discussion, four general flowing artesian well seal types will be discussed.

Seal type 1: Low pressure head, low hydraulic conductivity

Seal type 2: Low pressure head, high hydraulic conductivity

Seal type 3: High pressure head, low hydraulic conductivity

Seal type 4: High pressure head, high hydraulic conductivity

Flowing wells with high pressure heads generally must be sealed using either concrete or a cement grout mixture, since a bentonite seal is unable to withstand the pressure and will ultimately fail. The use of an expanding grout admixture is essential to provide a controlled swell to the concrete or grout to assure that the mixture fully fills the seal area and does not develop shrinkage cracks. An additional consideration is whether the flowing wells are uncased or cased. For cased wells, further consideration must be given to the condition of the casing and whether the annular space between the casing and the adjacent strata have been properly sealed when the casing was installed.

Flowing wells in high hydraulic conductivity flow systems must be temporarily dewatered to stop overflow during seal construction. Placement of concrete or grout in water is acceptable, however placement in **flowing water** will result in erosion of the seal material. Again, the use of an expanding grout admixture is essential for successful sealing of these flowing wells.

A final consideration is on sites where temporary dewatering to facilitate sealing is unachievable due to terrain (flat topography areas). For these sites, the installation of casing may be required and a two-part seal may be necessary with dewatering initially occurring in the cased part of the well.

3.3.4.1 Flowing Well Seals - Low pressure head, low hydraulic conductivity wells

Flowing well seal design considerations are relatively straightforward for this type of well since the combination of low pressure and low hydraulic conductivity generally translates to very low flow rate wells with slow rates of pressure increase against the seal over time. The very low flow rate and slow pressure increases usually allow the well to be effectively sealed by direct injection methods where either concrete, grout or bentonite is "tremmied" directly into the well, beginning at the bottom of the well and continuing to the surface. This is the only flowing well condition where bentonite-only seals may be effective.

Case studies:

Foreman (1993) designed and constructed a seal to abate a flowing well condition which had occurred at a recently constructed industrial water supply well which was developed into a low pressure flow system having low hydraulic conductivity. The well was sited next to a manufacturing facility in Clearfield County, PA. Both the measured pressure head and the flow rates were very low and adjacent well sites that were just slightly topographically higher did not exhibit flowing artesian conditions. Unfortunately, the adjacent wells were not "accessible" and we were unable to use these wells to locally dewater the flow system at the flowing well site. However, the characteristics of the flow system were such that a decision was made to proceed with the seal construction without the benefit of temporary dewatering and abatement of flow. Since the well was recently drilled and had

not been cased, there was no need to ream the well. Casing was set to a level where sufficient depth was available to construct a seal with a grout basket installed at the casing base (although a packer could have been used).

Sealing of the flowing artesian well was accomplished by initial placement of bentonite pellets into the annular space between the well and the casing. After the initial swelling of the bentonite temporarily abated the flow, a high strength concrete mixture was poured into the remaining annular space until the annular space was filled to the ground surface. No reoccurrence of the flowing condition was observed at the well site.

3.3.4.2 Flowing Well Seals - Low pressure head, high hydraulic conductivity wells

Flowing wells developed in regional synclinal flow systems with low pressure and high hydraulic conductivity may have highly variable flow rates due to regional connectivity. The well must be purged of casing by reaming or using churn drills unless it has been found that the annular space between the casing and strata was fully and properly grouted. Sealing considerations for these types of wells requires positive measures to temporarily abate the flowing condition at the well surface. Typically this is accomplished by "local" dewatering the flow system near the flowing well by pumping from adjacent wells. Once the flowing condition has been temporarily abated, sealing work can begin. The well can now be sealed by tremmie placement of either a high strength concrete or a high penetration grout mixture, depending on the characteristics of the well and aquifer. Addition of an expanding grout admixture is essential to provide a controlled swell to the concrete or grout assuring full sealing and to prevent development of shrinkage cracks. The high hydraulic conductivity condition often translates to high volume pumping efforts to locally dewater the seal area and also requires continuous dewatering during sealing. The low pressure condition allows the "local" dewatering to be terminated within 7 days following seal placement. This time period is necessary to assure concrete/grout set-up.

Case Studies:

Foreman (1996) designed and constructed several seals to abate flowing well conditions which had occurred at several recently constructed monitoring wells developed in the lowwall area adjacent to a reclaimed surface mine in Centre County, PA. The reclaimed surface mine was developed below regional drainage levels and the mining had

breached a regional confining member. During operations, the company had to pump and treat excessive volumes of water to maintain a condition where mining was feasible. Following completion of mining, backfilling and revegetation, a final cut impoundment was developed as a wetland. The regional flow system underlying the mine site prior to mining was no longer being pumped and immediately began to rebound. This flow system recharged the spoil and eventually began to discharge along the lowwall as the regional flow system continually attempted to establish pressure equilibrium with the atmosphere.

Discharge rates from this reclaimed mine site varied from very low flows (6 L/min) to very high flows (>1000 L/min) based on the recharge into the regional system. The high flow rates were not due to high pressures, but were due to the high hydraulic conductivity of the flow system where regional inflows could move very rapidly to this discharge area. As part of a passive treatment construction program, the discharge from the regional flow system was temporarily abated by pumping and treating the final cut wetland and regionally dewatering the flow system. This also stopped flows from the monitoring wells.

Sealing of the flowing artesian well was accomplished by tremmie placement of concrete down the drill hole until the hole was filled to the surface. The concrete was a high strength mixture that had an expanding grout admixture added to assure complete sealing. The dewatering continued during the construction of the passive treatment systems and no reoccurrence of the flowing condition was observed at any of the monitoring wells.

3.3.4.3 Flowing Well Seals - High pressure head, low hydraulic conductivity wells

Flowing wells developed in regional synclinal flow systems with high pressure and low hydraulic conductivity typically have low flow volume with flow sustained year-round. The well must be purged of casing by reaming or using churn drills unless it has been found that the annular space between the casing and strata was fully and properly grouted. Sealing considerations for these types of wells requires positive measures to temporarily abate the flowing condition at the well surface. Typically this is accomplished by "local" dewatering the flow system near the flowing well by pumping from adjacent wells. Once the flowing condition has been temporarily abated, sealing work can begin. The well can now be sealed by tremmie placement of either a high strength concrete or a high penetration grout mixture, depending on the characteristics of the well and aquifer. Addition of an expanding grout

admixture is essential to provide a controlled swell to the concrete or grout to assure full sealing and to prevent development of shrinkage cracks. The low hydraulic conductivity translates to small pumping efforts to dewater the seal area. The high pressure condition requires that "local" dewatering be continued up to 28 days following seal placement. This time is necessary to assure full concrete/grout strength.

Case Studies:

Beck and Foreman (1985) designed and constructed a seal in a flowing artesian well at the Oneida Mining Co. - Dilltown facility in Indiana County, PA. This flowing artesian well was inadvertently developed as part of an on-going hydrogeologic investigation at the site. The well was initially drilled to a depth of approximately 17 m to provide monitoring capabilities for the adjacent surface facility area, specifically the rotary dump loading site. The drilling at the well site penetrated approximately 10 m of intact claystone and shales and the drilling continued for an additional 7 m until reaching a large, regional sandstone member which was believed to be the immediately underlying aquifer.

After drilling was completed, the well began to flow steadily and the discharge had both acidity and sufficient metals concentrations to warrant abatement, otherwise the company would have been required to treat the discharge from the well to meet effluent standards. Since the well was recently drilled and not cased, there was no need to ream the well. The flow system from which the well received recharge was dewatered using an existing, nearby water well which was sited topographically upgradient and had no history of flowing artesian conditions. This temporarily abated the discharge at the flowing well. Sealing of the flowing artesian well was accomplished by tremmie placement of concrete down the drill hole until the hole was filled to the surface. The concrete was a 4000 psi mixture that had an expanding grout admixture added to assure complete sealing.

Following the placement of the concrete seal in the flowing well, the dewatering continued for about one month to minimize pressure on the concrete seal and to assure that the concrete seal had fully cured and reached ultimate design strength. The dewatering was terminated after one month and the sealed well was monitored for several years. No reoccurrence of the flowing condition was observed.

3.3.4.4 Flowing Well Seals - High pressure head, high hydraulic conductivity wells

Flowing wells developed in regional synclinal flow systems with high pressure and high hydraulic conductivity typically have very high flow rates with flow sustained year-round. The well must be purged of casing by reaming or using churn drills unless it has been found that the annular space between the casing and strata was fully and properly grouted. Sealing considerations for these types of wells requires substantial positive measures to temporarily abate the flowing condition at the well surface. Typically this is accomplished by "local" dewatering the flow system near the flowing well by pumping from adjacent wells. Once the flowing condition has been temporarily abated, sealing work can begin.

The well can now be sealed by tremmie placement of either a high strength concrete or a high penetration grout mixture, depending on the characteristics of the well and aquifer. Addition of an expanding grout admixture is essential to provide a controlled swell to the concrete or grout to assure full sealing and to prevent development of shrinkage cracks. The high hydraulic conductivity and high pressure translates to a very high volume, continuous pumping effort to locally dewater the seal area and maintain the drawdown. The high pressure condition requires that "local" dewatering be continued up to 28 days following seal placement. This time is necessary to assure full concrete/grout strength.

Case Studies:

Foreman, Moore and Foreman (1984) designed and constructed a flowing well seal at a flowing artesian well known as "Big Bertha" located in Butler and Venango Counties, PA. This well had been identified as a major pollutional source in Slippery Rock Creek. Hydrogeologic studies of the abandoned gas well performed during the design stage determined that flows from the well varied annually from approximately 75 L/min (20 gpm) to nearly 680 L/min (180 gpm). The chemistry of the well was strongly pollutional and representative of AMD and not saline water which would be typically anticipated from an abandoned gas well. The hydrogeologic study also identified five separate flow systems that recharged this well. Discrete interval chemical samples and dye studies jointly conducted with the USGS determined that the upper two flow systems were strongly pollutional and had

highly variable inflow rates to the well, while the lower three flow systems contributed approximately 65 L/min (17 gpm) of steady state inflow to the well and these were not pollutional.

The flow systems were strongly confined at the flowing artesian well. Geologic correlation of the strata associated with the upper two flow systems indicated that the probable source of the AMD in the flow systems was originating from a nearby abandoned mine and was traveling both topographically and structurally downgradient towards the well. A decision was made to "partially seal" the flowing well such that inflow from the upper two pollutional flow systems would be abated while the lower three flow systems would be allowed to recharge the well, thus creating a steady-state, non-pollutional flowing artesian well which would discharge alkaline water into Slippery Rock Creek at 65 L/min (17 gpm). The well was first purged and reamed. New casing was set to a stratigraphic level below the base of the upper flow systems and the annular space was then sealed using an expanding grout. Placement was facilitated by "downhole pump" dewatering techniques.

3.3.5 Grout Curtains / Walls

Grouts can be used to separate acid-producing rock and groundwater. Injection of grout barriers may significantly reduce the volume of groundwater moving through spoil and thereby greatly reduce the amount of AMD coming from a site.

Case Studies:

Gabr et al. (1994) characterized the groundwater flow of an acid-producing reclaimed site where a 1.5-m thick wall was installed by pumping a mixture of class F fly ash and portland cement grout into vertical boreholes near the highwall. After two years, the grout wall reduced groundwater inflow from the highwall to the spoil by 80%, resulting in one of two seeps completely drying up and substantially reducing the flow of the other seep.

Foreman, Ward and Schettig (1973) designed and constructed a grout curtain along Interstate 80 (Clarion County, PA) to abate significant seepage through an inadequate coal barrier pillar and overlying strata which was causing slippage of the road cut highwall and AMD pollution to a tributary draining to the Clarion River. The grout curtain was developed by drilling grout injection holes along the top of the road cut and then grouting was done continuously along the length of the cut from the base to the ground surface. Following

completion of the grouting, no further discharges or slippage was observed. Foreman, Hong and Ward (1977) designed and constructed a slurry trench to abate the discharge from an abandoned deep mine (Mercer County, PA). The slurry trench was developed along the peripheral outcrop barrier of the mine and was excavated from the surface using large backhoes. The trench was then backfilled with a soil-bentonite stabilized slurry which provided a hydraulic barrier to prevent lateral discharge from the abandoned deep mine. The slurry-trench seal was effective since there was no discharge following construction and the deep mine became fully inundated.

Foreman and Glenn (1980) designed and constructed a slurry trench to abate the discharge from an abandoned deep mine (Clarion County, PA). The slurry trench was developed along the peripheral outcrop barrier of the mine and was excavated from the surface using large backhoes. The trench was then backfilled with a stabilized soil-cement slurry which, when set-up, provided a relatively impervious barrier to prevent lateral discharge from the abandoned deep mine. The slurry-trench seal was effective since there was no discharge following construction and the deep mine became fully inundated.

3.3.6 Underground Disposal

The disposal of AMD related mine wastes in underground mines has historically included the disposal of mine gob, mine treatment sludge and flyash. The mine gob is typically disposed when excessive partings in the coal seam and excess roof/floor rock are removed during deep mining operations. This material often has potential to cause AMD and is typically placed in cross-cuts where access is not needed.

Mine treatment sludge is typically placed in isolated mine reservoir areas where the precipitate rich sludge will not create future treatment problems if the metals are redissolved in the mine water since the reservoir is isolated from the mine pumps.

The disposal of fly ash holds significant promise since this material may prove to be doubly-beneficial in instances where backstowing to prevent subsidence effects can be accomplished with a material that may also produce some alkalinity to the water.

Case Studies:

Mine gob disposal is a common practice in underground mines throughout the world. The return of alkaline mine treatment sludge to isolated mine reservoirs was done throughout

the 1980's by several underground mine operators with good success. No long term studies are known for fly ash disposal into deep mine works.

3.3.7 Injection

The placement of acid-producing materials, AMD or their altered product into the subsurface through a vertical drilled hole has been an effective method of disposal in some situations. The practice of drilling a well down to porous rock strata and then injecting fluids into the underground formation is a technique that has only recently become popular for dispersing pollutants to a confined subsurface area. The most favorable geologic depths present in the Appalachian region dictate a depth range of 1,000 to 2,000 m. This technique is significantly limited by factors that would either allow the injected waste to escape from the containing strata and polluting ground waters or cause other secondary effects. The actual space available for deep well disposal is limited, since the space used by injected material must be made by displacing other materials (ground water) and increasing rock pressures. Increases in deep geologic pressures can, and have, caused ground movement. Possible long term chemical reactions between the strata and the injected waste pose another constraint. While areas of oil and gas deposits have favorable strata for injection, all of the abandoned wells have to be located and plugged. Another limitation is that this technique does not destroy the pollutant, but transfers it from a place of immediate concern to a place where its presence is not anticipated at the time to be of concern. The difficulty in obtaining adequate sub-surface geologic information and the lack of knowledge of how the geology would react to injected wastes are the most important reasons for not being able to adequately anticipate short and long term effects. This technique is regulated by the Federal Safe Drinking Water Act and it appears that the general use of this technique in areas with suitable geology is not warranted at this time.

Case Studies:

There had been six active deep wells handling acid waste in Appalachia. The advent of disposal wells in Appalachia is relatively new and such information as has been obtained is not publicized. Determination of the capacity (rate) of a well requires drilling the well and running a pressure test to determine the capacity curve. It is reasonable to place an upper limit of approximately 4 million L/day (1 Mgal/day) on individual well capacity for any

reasonable injection pressure. Thus deep well disposal does not appear to be a reasonable control technique for unconcentrated acid mine drainage. Concentration techniques such as reverse osmosis, evaporation, or ion exchange, however, can use it successfully.

3.3.8 Inert Gas Blanket

This involves the placement and retention within an underground mine of an inert gas (a gas that is not reactive in the AMD forming process). Such gases include carbon dioxide, nitrogen, and methane. Inert gas blanketing of abandoned deep mines has great promise, since it prevents the oxidation of acid material and thus does not produce residues for disposal such as from neutralization. This process can be used based on the dependability and security of mine seals. If the mine can be sealed completely, little additional makeup gas will be necessary after the initial injection. If the mine is only partially sealed, considerable amounts of gas will be necessary to keep the underground mine atmosphere filled with inert gas. As soon as oxygen is readmitted, acid is produced.

Case Studies:

Case study summaries are not available at this time.

3.3.9 Regulated Pumping

Regulated pumping is the discharge of AMD at volumes, rates, times and locations so that the contaminating effects will be minimized. Pumping is applied largely to active mines to regulate mine water depths. Most pumping of drainage is accomplished over a short period of time each day in order to avoid pumping during periods of peak use. There is an attempt by regulatory agencies to require pumping continuously to avoid slugs of waste being discharged to streams.

Case Studies:

Case study summaries are not available at this time.

3.3.10 Stream Flow Regulation

Stream flow regulation is the containment and release of stream waters at volumes, rates, times and locations so that the contaminating effect will be minimized. Controlled releases of stored water at periods of high concentrations of mine drainage in streams would disperse the pollutants to predetermined concentration levels. The types of reservoirs that would be considered effective for mine drainage control would be similar to those designed

for low stream flow augmentation. This is an area control technique particularly applicable where there are a great many small sources of contamination in a watershed. Much additional detailed information needs to be determined on the acid yield, the weighted acidity, by day or by week for contaminated streams or watersheds, as well as the weighted alkalinities of the uncontaminated streams in order to apply this flow control technique. Once the required reservoir has been determined by equating alkalinity to the actual acidity, the costs can be estimated.

Case Studies:

Case study summaries are not available at this time.

3.3.11 Dispersion and Containment

If acid mine drainage pollutants can be reduced to tolerable concentrations or manageable volumes, then dispersion and containment techniques offer an option for the effective control of mine drainage pollution under some conditions.

Case Studies:

Case study summaries are not available at this time.

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